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# Mapping coral reef environments: A review of historical methods, recent advances and future opportunities

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Coral reef environments support high levels of marine biodiversity, they are important sites for coastal habitation and they provide a range of goods and ecosystem services such as nearshore fisheries, economic revenue from tourism and breeding sites for seabirds and turtles. Mapping is a fundamental activity that underpins our understanding of coral reef environments and helps to shape policies in resource management and conservation. This is particularly the case for quantifying the area of landcover types associated with reef environments, including coral patches, seagrasses and mangroves, but also for monitoring how these change over time and modelling how spatial patterns apparent on reefs are related to environmental drivers. Field techniques and aerial photography have historically played a crucial role in mapping coral reef environments, which has recently seen a transition toward the processing of satellite remote sensing images. This paper examines a series of maps produced of Low Isles, the most mapped island on the Great Barrier Reef, to review historical methods for mapping coral reefs because of the critical importance of understanding how past maps were made, which determines appropriate uses to which they can be put. Recent advances and future opportunities for the application of mapping technologies to coral reefs are also evaluated, including the use of unmanned aerial vehicle (UAV) platforms for airborne surveys, delivery of information through web-based platforms and improvements in the quality of information for making and presenting maps. Maps have transformed the way we have responded to both historic and contemporary coral reef problems. This timely review communicates how maps, and the fast growing technologies that are employed to produce them, are central to our understanding of coral reef environments. Recent advances that may drive exciting new environmental management tools are identified.

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## Abstract

Coral reef environments support high levels of marine biodiversity, they are important sites for coastal habitation, and provide a range of goods and ecosystem services such as nearshore fisheries, economic revenue from tourism and breeding sites for seabirds and turtles. Mapping is a fundamental activity that underpins our understanding of coral reef environments, and helps shape policies in resource management and conservation. This is particularly the case for quantifying the area of associated landcover types including islands, coral patches, seagrasses and mangroves, monitoring how these change over time and modelling how spatial patterns apparent on reefs are related to environmental drivers. Field techniques and aerial photography have historically played a crucial role in mapping coral reef environments, which has recently seen a transition toward the processing of satellite remote sensing images. This paper examines a series of maps produced of Low Isles, the most mapped island on the Great Barrier reef, to review historical methods for mapping coral reefs because of the critical importance of understanding how past maps were made and appropriate uses to which they can be put. Recent advances and future opportunities for the application of mapping technologies to coral reefs are also evaluated, including the use of unmanned aerial vehicle (UAV) platforms for airborne surveys, delivery of information through web-based platforms and improvements in the quality of information for making and presenting maps. Maps have transformed the way we have responded to both historic and contemporary coral reef problems. This timely review communicates how maps, and the fast growing technologies that are employed to produce them, are central to our understanding of coral reef environments. Recent advances that may underpin exciting new environmental management tools are identified.


## I Introduction

'Coral reef environments' are broadly defined as low lying islands that are often vegetated, the coral reef platforms upon which they sit and associated structures, such as barrier and ribbon reefs. Reef platforms provide a shallow, habitable surface for colonisation by a veneer of diverse and dynamic reef-dwelling organisms including hard and soft coral, sponges and invertebrates. A coral reef platform is a three-dimensional structure that has built up and continues to grow over decadal to millennial time scales as a result of the accumulation of calcium carbonate laid down by corals and other organisms (Hubbard, 1997; Montaggioni and Braithwaite, 2009). The shallow flats and slopes of reefs support dense assemblages of light-dependent communities such as algae, both alive and dead corals, sponges, crustaceans and sedentary invertebrates (Done, 1983). Seagrasses are common features of intertidal zones, and play an important role in stabilising reef island shorelines. They impart stability through their extensive horizontal rhizome root systems, which form discrete clumps, patches or meadows, and can extend over several kilometres (Robbins and Bell, 1994). Further up the intertidal foreshore, salt-tolerant, woody mangroves form forests or shrub land that links terrestrial and marine components of reef islands (Heumann, 2011). The integrity and longevity of the many goods and ecosystem services that are derived from coral reef environments are inherently reliant on these different components of their physical structures, working both in isolation and together. These goods and ecosystem services include the provision of land for coastal habitation, seabird and turtle breeding sites, marine habitat for nearshore fisheries and economic revenue from tourism.

Mapping helps us to understand and manage coral reef environments. The synthesis and expression of information through maps has a long history of improving our understanding of how environmental processes shape coral reef environments. For example, hydrographic charts showing the global distribution of fringing, barrier and atoll reefs were used by Darwin (1842), Guppy (1888), Agassiz (1903) and Joubin (1912) to develop theories of reef evolution in relation to the Coral Reef Problem, which examined how coral reefs form and evolve around subsiding volcanic land masses (Davis, 1928; Stoddart, 1994). By the mid-twentieth century, reefs were recognised as complex spatial units comprising an array of geomorphological and ecological features. This brought about a transition in modes of engagement with reefs from ship-borne and ocean basin scales of observation to field-based surveys and more detailed mapping of individual reefs, along with their ecological communities. After World War II, field mapping of coral reefs was characterised by *'the progressive refinement of the mapping of surficial features of reefs, and especially of reef islands that became recognised as important components of the wider reef system'* (Spencer, 2008: , pg 869). Examples of this transition include maps of the surficial morphology and reef character associated with the expeditions to Funafuti atoll (David, 1904; David and Sweet, 1904), the islands and reef flats of the Bay of Batavia, Indonesia (Umbgrove, 1928) and the maps produced by two major coral reef expeditions: the 1928-29 Expedition to the Great Barrier Reef and the 1929-30 Snellius Expedition to eastern Indonesia (van Aken, 2005; Van Riel and van Riel, 1934). This was accompanied by a growing awareness of the valuable and fragile nature of coral reefs, such that they were increasingly seen as threatened environments, as opposed to threats to human activity (Sponsel, 2015). Contemporary mapping exercises are therefore driven by environmental management and conservation objectives, such as global syntheses of healthy and unhealthy ecosystem statuses ('bright and dark spots') given local environmental and socioeconomic conditions (Cinner et al., 2016).

At the most basic level, maps provide an inventory of the form of an island, reef or associated marine community at a particular snapshot in time (Goodman et al., 2013). A time series of maps may be used to monitor how coral reefs have changed over time (Hedley et al., 2016). At a higher level of complexity, a model may predict reef behaviour in the future (see Table 2 for examples). While maps have historically been published in atlases, the advent of digital mapping has seen online portals increasingly delivering electronic maps in dynamic format to a wide audience, for example, through the U.S. National Oceanographic and Atmospheric Administration's *Coral Reef Information System* (CoRIS, 2005). Maps enable managers to assess the regional biophysical status of coral reefs, facilitating status comparisons within and between regions and enabling changes to be monitored over time (Hamel and Andréfouët, 2010; Lourie and Vincent, 2004; Wabnitz et al., 2010). Information contained in digital maps is particularly useful for spatial conservation planning, for example, to evaluate candidate sites for protection (Roberts et al., 2003; Dalleau et al., 2010; Wilson et al., 2009). Finally, digital maps are increasingly being treated as datasets in their own right, to be interrogated using specialised software to better understand spatial patterns in coral reef environments, for example, in the characterisation of benthic habitat and geomorphic zonation (Hamylton et al., 2012).

This paper reviews historical methods and recent advances in mapping coral reef environments. A detailed case study describing historic and recent mapping campaigns at Low Isles, the island on the Great Barrier Reef with the longest historical record of mapping activity, illustrates a range of approaches to mapping through field survey and their associated advantages and disadvantages. These include plane-table, theodolite, compass-traverse and pace surveys, as well as contemporary field campaigns for the purpose of ground-validating remotely-sensed imagery. Emergent mapping technologies such as the use of unmanned aerial vehicles UAVs) that hold promise for application to coral reef environments and future opportunities for technological developments are evaluated. Such a review is timely and important because the application of contemporary geospatial technologies to coral reef environments now comprises an entirely different and unrecognisable set of activities to the historical cartographic field methods. In light of such marked technological transformations, it is critical to understand the means by which maps were historically produced in order to fully appreciate their value and understand the uses to which they can be put.

## *1 Mapping, monitoring and modelling in coral reef environments: An overview*

Figure one illustrates a framework for mapping, monitoring and modelling in coral reef environments. Thich provides a useful organisational structure for the present review. Applications build through a hierarchy of analytical depth from mapping (making a map), to monitoring (making and comparing multiple maps), to modelling (using a map as a dataset in its own right). These offer a collective view of the utility of maps, emphasising the way in which a transition through these different levels of analysis adds value to spatial information. This value derives from the increasing degree of customisation for interrogation to inform conservation management decisions, elucidate the impacts of climate change in coral reef environments and manage the effects of a growing human population.

# II Historical approaches to mapping coral reef environments

Table 1 summarises a range of mapping approaches that were widely applied to coral reefs in the early twentieth century, as well as more recent technologies. Some of the earliest published 'sketch maps' of coral reefs were produced by placing a plane table at a series of locations around the reef. These locations afforded views of landscape characteristics such as a lighthouse, beach rock or mangrove stands. The plane table was set at a reference point, and multiple ray lines were recorded along a site-rule to mark both the direction and distance of an object of interest. This simple and practical instrument for developing basic outline geographical illustrations for scientific papers compared favourably against others in relation to speed for a given order of accuracy and dependence on the assistance of other workers (Debenham, 1936).

A manuscript from the Department of Geography, University of Cambridge describes the *1928-29 Great Barrier Reef Expedition* plane table as: *"a drawing board about 15 x 20 in (38 x 51 cm), mounted on a stout camera tripod, clamped by a heavy screw fitting with large wings. The sighting instrument, the alidade was a plain 15-in (38-cm) wooden ruler stiffened by a brass strip fastened to the bottom edge; the sights were fashioned out of two long brass hinges, and folded down for packing. The foresight was made of a fine wire soldered into place, but was later replaced by a simple waxed thread. An ivory scale rule and trough compass completed the equipment. The whole was packed in a large double packet of stiff canvas, one for the plane table and the other for spare Bristol board sheets of drawing* *paper. It all fitted neatly and tightly together, the tripod carried separately. This home-made plane table was in constant use for two summers and came to no harm".* (Speak, 2008: , p.6).

Plane table sketches were later made more precise by introducing a theodolite to measure angles at high precision, which consists of a mounted telescope that is movable in both a horizontal and vertical plane. Precise angular measurements can be made when the telescope is pointed towards features of interest. Meandering coastlines and beach ridges were triangulated through a framework of points and lines that were later removed from the finished map. The curve of a coastline could be sketched by superimposing sighted lines over natural features and the position of an emergent coral boulder could be established across a reef flat by sighting the boulder from either end of a fixed baseline and measuring angles toward it. Subsequent plotting of the points to scale, or use of trigonometry determined the exact boulder location as the third corner of a triangle with one known side length and two known angles. This process conducted through the build-up of a large triangulation network was fundamental to field mapping and large-scale land survey in the early twentieth century.

For a more mobile approach at sites where a surveyor could easily access the reef system, compass traverse surveys were frequently used because of their relatively rapid deployment. Traversing is the measurement of the direction and distance from a known position to an unknown location. This proceeds in a loop with the final measurement an extension from the endpoint back to the beginning, such that a closure error can be calculated (Debenham, 1937). The accuracy of the technique could be increased by substituting paces which were calibrated against approximate distances with tape measurements of distance.

Compass traverse surveys required extensive field observations that relied on the subjectivities of the fieldworker, and the features they were interested in mapping. Field notes recorded landforms, bearings and distances that were subsequently plotted either directly with a protractor, or projected onto a rectangular coordinate grid. Once a network depicting the major landform features has been established, additional detail including cay composition and vegetation, was later filled in by transects normal to the shore (Stoddart, 1962: pg 129 Appendix "Surveying").

# III Remote sensing technologies for mapping coral reef environments

Broadly defined, remote sensing is the acquisition of information about a given feature of interest from a distance (Rees, 1999). Remote sensing techniques may employ passive sensors (those sensing naturally occurring radiation) or active sensors (those emitting and sensing their own energy pulse, for example in the form of light or sound waves). They may be operated from a range of platforms, including planes, satellites, drones, boats and automated underwater vehicles (Hamylton, 2017). Visual interpretation of aerial photography represents the earliest means by which remotely sensed datasets were employed for reef mapping. The use of aerial photographs for mapping coral reef environments initially relied on images collected by extensive aerial surveys that were undertaken by the military in WWII (Teichert, 1995). Many low angle, oblique aerial photographs were captured during the War to chart beach landings and locate small Pacific islands. These were later increasingly used to track morphological changes and the transfer of waves over reef platforms (Steers, 1945). Walter Adey's maps of shallow algal ridges in St Croix provide an early example of the use of oblique aerial photography to map and interpret features in coral reef environments (Adey, 1975).

The first earth observation satellite, TIROS 1, was launched by the North American Space Agency in 1960, an infrared weather observation satellite. Earth observation satellites revolutionised reef mapping because for the first time, large geographic areas in the field of view afforded by such a high altitude (ca 150 $km^2$) could be simultaneously mapped and these same areas could be revisited on a subsequent orbit to permit an evaluation of change.

Optical remote sensing satellites provide a synoptic portrait of the Earth's surface by recording numerical information on the radiance measured from a series of picture elements (pixels) across a number of spectral bands, i.e. within discrete wavelength portions of the electromagnetic spectrum (Green et al., 2005). Passive sensing instruments focus incoming solar radiation onto a CCD detector to create an electronic response, which is digitally recorded in a pixel array. The amount of information provided in these datasets, particularly the collective statistical properties of the multiple reflectance values associated with the image pixels offer an opportunity for interpretation using automated approaches. For example, image classification algorithms generate thematic by categorising reflected light recorded in imagery as representations of real-world objects (Mather and Koch, 2011). Categorised responses of pixels are subsequently placed into user-defined groups that form the legend of a digital map.

The interpretation of remote sensing images is often made difficult by the presence of clouds that obscure features of interest, absorption and scattering of light in the atmosphere, limited depth of light penetration into the water column, variation in water quality across a single image scene and backscatter of light causing sun glint from the sea surface. It is necessary to pre-process remotely sensed imagery to remove these artefacts as much as possible before interpreting it in terms of the seafloor. A range of pre-processing techniques including atmospheric, water column and glint correction have been developed to improve the accuracy to which coral reef environments can be mapped from airborne and satellite remote sensing images (Mumby et al., 2004).

## *3.1 An overview of remotely sensed maps of coral reef environments*

The first global overview of the location, extent and distribution of reef systems based on remotely sensed information was compiled in the *World Atlas of Coral Reefs* published by the *United Nations Environment Programme World Conservation Monitoring Centre* (Spalding et al., 2001). The level of detail was largely determined by the availability and quality (scale, accuracy, precision) of marine charts across different reef regions. The consistency offered by satellite remote sensing for mapping coral reef environments became apparent with the launch of the Landsat program, which began collecting consistent earth observation satellite imagery in 1972, and remains today the best suite of continuous sensors between which comparisons can be drawn. The Millennium Coral Reef Mapping Project (MCRMP) was established in 2004 and has examined more than 1600 Landsat 7 ETM+ satellite images (spatial resolution 30 m x 30 m; with 4 useful wavebands for mapping coral reef environments) worldwide. Photo interpretation techniques have been employed to map the reef systems of the major reef provinces of the world using a globally applicable and consistent typology of 800 classes (Andréfouët et al., 2006). The geomorphic focus of this project exemplifies the utility of the Landsat sensor in relation to coral reef environments- the coarse 30 m resolution enables high level landform mapping of features such as 'mainland', 'barrier land' and 'atoll rim'; which are illustrative of the level of detail to which island environments can be resolved from this sensor. While the approach cannot capture finer scale detail of benthic communities inhabiting reef platforms, the undeniable value of the Landsat Program for mapping reef environments is evident in the global consistency achieved from this campaign.

At the regional scale (i.e. groups of reef platforms), airborne and satellite based campaigns have further increased the level of detail to which coral reef groups can be mapped. Notable examples including the use of Landsat TM and Compact Airborne Hydrographic Imager (CASI) to develop regional classifications of benthic reef habitats in the Caribbean (Mumby and Harborne, 1999) and CASI airborne surveys of the 11 Amirante islands in the Seychelles (Spencer et al., 2009). Higher resolution QuickBird satellite images have been used to map of Saudi Arabian Red Sea marine habitats (Bruckner et al., 2013). In the southern Great Barrier Reef, the 21 reefs of the Capricorn-Bunker Group have been mapped in detail to support estimation of carbonate production across the archipelago (Hamylton et al., 2017). At a coarser level of detail, the Great Barrier Reef Marine Park Authority's dataset of 5376 features (e.g. mainland, island, cay etc.) was generated by classifying Landsat-7 images with independent helicopter surveys for ground control (Lewis et al., 2003; Hopley et al., 2007).

At the local scale, geographically focussed campaigns over the last decade have enabled much higher levels of detail to be achieved, often employing multispectral sensors such as Quickbird and WorldView-2 (pan sharpened resolution of 1m) to precisely and accurately map shorelines, mangroves, seagrasses and corals. These sensors are well suited to the classification of coastal features because of their relatively high spatial and spectral resolution. The launch of the WorldView3 satellite in 2014 with a spatial resolution of 1.24 m (0.31m pan sharpened) continued a trend of incremental improvements in the level of detail available from satellite-based multispectral remote sensors. This detail has translated into improved coral reef environment maps, including both emergent and submerged land cover (Collin and Planes, 2011; Collin and Hench, 2012). Local campaigns are often accompanied with extensive ground referencing exercises that tailor the thematic content of maps to specific areas, although the repeatability of such campaigns in other locales remains one of the strengths of the consistency associated with remote sensing datasets.

## *3.2 Upscaling fieldwork effort*

Remote sensing technology increases the output per unit effort in relation to fieldwork, information processing and the quality of the final map product. Fieldwork campaigns undertaken for the purpose of ground-validating remotely sensed imagery must generate spatially referenced records of land surface cover. These records may take the form of field notes, photographs, gridded or categorised entries along transects, video footage (above and underwater), or notes annotated onto maps (Roelfsema and Phinn, 2010). In- photographs or image spectra are often collected directly by a diver or snorkeler in the water. Working from a boat platform facilitates rapid access across large areas and operating instruments such as underwater cameras from cables allows deeper environments to be surveyed. In all cases, it is critically important that any observations can subsequently be located and plotted alongside other information, so a diver may tow along a GPS, or instruments may have internal GPS capabilities (see Figure 2).

In the Turks and Caicos, a remotely sensing mapping campaign was compared with a solely field based approach that used gridded survey and interpolation to derive a map product of comparable information content. Remote sensing was found to be cheaper, quicker and more accurate (Mumby et al., 1999)). The efficiency gains derived from using imagery to scale up local observations over broader geographic areas expand as the level of survey detail is inceased. For example, detailed quadrat surveys of seagrass and mangrove properties such as leaf area index, shoot density or standing crop can be reliably upscaled using remote sensing imagery (McKenzie et al., 2001). Another benefit that remote sensing technology has brought to planning field survey is the ability to visualise and delineate geographical areas of similar spectral characteristics within the remote sensing image which correspond to areas of homogenous ground cover. Detailed field survey within these areas will likely yield little variation in ground cover and therefore be redundant. Similarly, heterogeneous areas of high ground cover variability can also be identified where field survey can more profitably be focused, resulting in more efficient, targeted fieldwork campaigns.

The spatial referencing information associated with field records is most commonly recorded with a mobile global positioning system (GPS). The horizontal accuracy associated with commercially available devices has improved over the past twenty years (commonly ca.4-8 m). Improved accuracies (locational error <1 m) are possible using differential GPS technology to simultaneously model, and correct for, errors in the satellite signal. With the help of navigational devices, GPS technology can track the location of a person in the field and display this simultaneously on a monitor, overlaid onto a spatially referenced map or satellite image in real time. This offers the distinct advantage of enabling the fieldworker to visit sites deemed to be of interest on the basis of the remote sensing dataset (e.g. satellite image) that forms the foundation of the map itself.

## *3.3 Quality of the map product*

The quality of any map product can be assessed in relation to its accuracy, resolution, completeness and consistency. The notion of accuracy, the difference between the “true” character of a feature and the character recorded in the map, is dependent on locational and thematic factors. The advent of Global Navigation Satellite Systems (GNSS) in 1994 provided a foundation for GPS, which enabled accurate and rapid determination of horizontal and vertical position through trilateration. Prior to this, topographic level surveys were used to determine the absolute location of mapped features in relation to a known benchmark. Locational information associated with older maps was therefore reliant on the quality of the benchmark, as well as the surveying undertaken to establish the link between the benchmark and the network of mapped features. In contrast, sensors mounted onto a plane or satellite platform, track their location continuously using an inertial measurement unit (IMU) coupled with a high precision differential GPS. Fluctuations in the position of the IMU allow corrections for unintended movements of an aircraft during an aerial survey.

A comparison of the thematic accuracy of historical and contemporary maps of reef environments enables a critical appraisal of the older maps. For example, the northeastern Australian coastline including the Great Barrier Reef that was famously mapped by Captain James Cook in the late eighteenth century was compared to a recent mosaic of Landsat satellite images of the same length of coastline, projected using the same frame of reference. In places, an 80 k m offset was found to exist between the two (Hamylton, 2017), illustrating the extent to which technologies have developed over this time. While such comparisons emphasise the uncertainty inherent in older maps, such maps often represent the only information on the historical distribution and form of coastal features such as coral reefs.

Nevertheless, it is fair to suppose that most of the features on older maps were actually recorded in-situ, which adds an element of inherent reliability to their identification that is not present in maps derived from remotely sensed datasets, which rely more heavily on automated extrapolation of field effort. Accuracy estimates for classifications of remotely sensed data compare them to independently collected validation datasets to derive metrics, such as ‘overall accuracy’, the proportion of points correctly classified by the map, across all classes (Congalton, 1991). Such measures incorporate both spatial and thematic aspects of the map information.

The resolution of maps generated from remote sensing images has incrementally increased as sensor technology has developed. Landsat satellites provided the firsts widely available earth observation imagery with associated pixel dimensions of 30 m. While these were useful for mapping geomorphic landforms of reef and islands (e.g. reef slope vs reef flat), they were of limited utility for resolving finer scale detail such as individual reef patches. Lower altitude sensors are able to acquire higher the spatial resolution images, such that airborne remote sensing campaigns carried out from aircraft or drone platforms yield imagery of sub-metre pixel resolution that is becoming more widely available (see section IV).

Given the comparably large geographic scale of most remote sensing images, they are often able to deliver a “complete” dataset in the sense that they provide continuous, synoptic information and their aerial extent commonly covers entire reef systems. Comparable seamless coverage of information from field survey alone is impractical. In the aforementioned Turks and Caicos example, a coarse field survey of 152 m resolution would translate into 190,000 sites, which would take a survey team of three more than 8.5 years to complete, at a cost of £380,000 (Mumby et al., 1999). Although remote sensing images provide much more extensive, continuous information, features may be obscured by clouds in images derived from satellite platforms, and areas subject to wave breaking such as beaches and reef crests are commonly termed “white ribbon” areas because the seafloor is obscured by breaking waves. Remote sensing images are also remarkably consistent in their information content because each grid pixel contains spectral reflectance responses from multiple image wavebands.

# IV Mapping from unmanned aerial vehicles (drones)

Drones are effective for mapping coral reefs at geographic scales that lie between the are typically covered by SCUBA or snorkelling surveys and those typical of airborne or satellite mapping (Casella et al., 2017). The potential for unmanned aerial vehicles (UAVs) for collecting aerial photography of coral reef environments has been recognized since the early 1980s (Scoffin, 1982). Airborne platforms can be operated from the ground and programmed to fly autonomously, without an on board pilot, along predetermined flight plans (Figure 3). The images are collected looking vertically downwards (i.e. at nadir), or across at an oblique angle. To date, platforms such as kites, helicopters, blimps or balloons have been used for this purpose, although drones are now much more widespread and affordable (Klemas, 2012; Scoffin, 1982).

Reductions in the size and weight of hyperspectral cameras, LiDAR, synthetic aperture radar and thermal infrared sensors have made it feasible to operate these sensors from an array of airborne platforms (Klemas, 2015). Greater control over deployments allows UAV surveys to target specific features of interest (e.g. a sand cay on top of a broader reef platform, see Figure 3b), and timed to coincide with favourable weather windows. Greater frequency of coverage is also achievable, for example, to survey at different points in the tidal cycle of a given day. Closer proximity of the sensor to the target enables the collection of more detailed images at a greater spatial resolution, and sensor spectral specification can be optimised for detecting underwater features (i.e. en emphasis can be placed on shorter wavelength bands that penetrate coastal waters).

One disadvantage of UAV platforms is that they collect images with a relatively restricted spatial extent of coverage in comparison to satellite imagery. Satellite images typically covera ground footprint of 50 – 100 $km^2$, which can incorporate several reef platforms. Comparable areas must be captured from a UAV over several flights due to shorter flight lengths because of battery power. Large areas must be surveyed along multiple pre-determined flight lines. Resulting images are mosaicked together by identifying common ground features falling in areas of overlap between adjacent lines. This introduces a need to process images before they can be interpreted for mapping. UAV surveys are also dependent on good weather, particularly low winds as most drones are light (e.g. the DJI Phantom UAV model should not be flown in wind speeds above 15 $ms^{-1}$). They cannot be flown over populated areas or in areas used by other aircraft. A common issue in coral reef environments is that they also risk disturbing resident populations of seabirds that nest in island vegetation, such as noddies and terns. Despite UAV technology becoming more affordable and widespread for hobbyists over the last 5 years, operational licensing restrictions have historically limited their uptake among the coastal management and research community. Kites have therefore continued to be used as a platform for detailed mapping, for example, to collect images for mapping vegetation cover and the reef systems around Durai Island of the Anambas Archipelago Indonesia (Currier, 2015). Similarly, aerial photographs have been collected using parasailing photography around Kish Island (Persian Gulf) and used to reliably map Acropora and Porites corals through visual interpretation (Kabiri et al., 2014).

Multiple surveys can be undertaken to assess how coastal features are changing and evolving. These can be helped by automated survey algorithms that can program UAVs to revisit the sites at regular time intervals (Pereira et al., 2009). Associated techniques for processing such datasets, e.g. structure from motion algorithms (Mancini et al., 2013) have expanded the type of information that can be incorporated in maps (see section 7.2 for a fuller discussion of their application). These have been successfully applied both above and underwaterto measure storm-driven changes in intertidal topography and sediment texture of a coral shingle cay (Bryson et al., 2013; Bryson et al., 2016) and the characterise the structural complexity of reef surfaces (Friedman et al., 2012).

The drive for cheaper, better and faster airborne imagery has placed a large emphasis on smaller, more cost-effective sensors. Recent designs for charge coupled device (CCD) cameras provide both higher spectral resolution sensors that are substantially smaller, more compact and less costly than their predecessors (Peterson et al., 2003). Recent development of inertial measurement units (Petovello, 2004) has improved the locational positioning associated with these datasets. As licensing restrictions for their operation have become less restrictive, this creates exciting new opportunities for enhancing and expanding their application in coastal environments.

## V Mapping in three dimensions: Island and reef digital elevation models

## 5.1 Mapping topography using structure from motion techniques

Structure from Motion (SfM) is a photogrammetric method for creating three-dimensional models of features and topography from overlapping two-dimensional photographs taken from many locations and orientations (Burns et al., 2015). The method can be applied to images taken above the water surface (e.g. by a drone or UAV), or beneath the water surface, either manually by a diver or from an autonomous underwater vehicle. The assumptions inherent in the method do not apply to photographs taken looking through a water surface.

It is often difficult to survey large areas at close proximity because of the greater number of images and associated processing burden that results as surveys are scaled over larger areas. Thus, while it may be possible to survey sand cays (typically <100 m across) at low altitudes, this may be difficult to achieve for coral reef platforms, which may be several orders of magnitude larger in size than the cay it supports (typically > 1 km across). The length of time required to survey an entire coral reef platform may present practical challenges associated with drone battery life and the availability of continuous favourable weather conditions (i.e. low wind speeds) for the length of time necessary to complete the survey. Alterations to light and water depth conditions for different parts of the survey may also occur due to movements of the sun and tides during this extended time window. Thus, there is a trade-off between generating better quality elevation models for smaller areas (i.e. individual landforms, such as island, spits or mangrove stands) and accepting lesser quality elevation models for larger areas (i.e. complete reef platforms).

## 5.2 Mapping underwater bathymetry using acoustic techniques

Optical remote sensing data or marine LiDAR can map bathymetry across shallow reef platforms (<30 m water depth) through clear water. Techniques for bathymetric mapping from optical imagery rely on the differential attenuation of light through the water column at different wavelengths (for a review, see Table 1 of Hamylton et al., 2015). Estimation accuracies depend on water quality and the variable albedo of different benthic covers, with darker substrates commonly being confused for deeper water depths (Mumby et al., 1998).

Marine and terrestrial Light Detection and Ranging (LiDAR) sensors combine high point density scanning laser altimetry data with high precision GPS to provide direct measurements of elevation in the form of detailed clouds of data points. These point cloud datasets are comprised of x, y, z information, where x and y relate to point longitude and latitude respectively, while z related to point elevation above a given vertical datum. These are 'active' sensors because they emit a pulse of light and analyse the return signal. Point clouds representing reflected light signals can be interpolated to produce a continuous elevation surface, or digital elevation model (DEM). LiDAR data provide information on reef geomorphology, rugosity, texture and bed-form geometry (Purkis and Brock, 2013). For intertidal applications, it is necessary to employ blue-green laser wavelengths that reflect off both terrestrial and submerged targets. Marine LiDAR datasets have the advantage that they allow continuous, uninterrupted mapping of beaches and underlying reef platforms across the 'white ribbon' zone of wave breaking (Leon et al., 2013). In addition, LiDAR pulses can be decomposed into their first and last point returns to assess coastal vegetation canopy structure (Nayegandhi et al., 2008).

Acoustic sonar methods profile underwater topography from the travel time between emission and reception of a sound pulse. As sound waves can propagate up to thousands of kilometres through water, they can be used for mapping deeper areas of coral reef environments (Riegl and Guarin, 2013). Sensors are either towed behind or mounted to the hull of a boat. They provide further information on the water body, sediment surface or the seafloor sub-bottom (sediment or bedrock) interior. Acoustic surveys are often undertaken as a series of parallel lines crossed by perpendicular 'tie' lines for validation. The line orientation and swath width are planned to provide complete coverage of a reef at the required spatial resolution. These are subsequently processed to generate cross-sectional profiles, topographic 3D bathymetric models of the surface area, seafloor mosaics of survey lines or volumetric representations (Riegl and Guarin, 2013).

Acoustic bathymetric survey instruments can be single beam echosounders, multibeam echosounders, side scan sonar and interferometric sonar. Single beam echosounders harness the time differential between the sent sound pulse and received echo, to measure distance from the seafloor. They are often interpolated to produce a continuous bathymetric representation of the seafloor. More complete profiles can be achieved using swath methods, which use an arrangement of single beam transducers to make up a wider swath. Multibeam sonar systems use beam forming and steering to generate a fan of sounding pulses originating from a single centralised transducer. Simultaneously mapping more than one location on the seafloor at a time reduces the ship time and costs for mapping the equivalent area of seabed with a single-beam echosounder. Ship-mounted or towed side scan SONAR instruments provide an underwater view of the seafloor from above by emitting two fan shaped beams from a transducer that is mounted from a towed platform. In reef environments, boats must be small with a shallow enough draught that the equipment can be safely towed across a shallow reef flat and navigated around coral bommies. By mounting transducers in linear arrays, side scan systems produce images representing seafloor texture inferred from scaled backscatter coefficients (the ratio of the intensity of sound scattered per unit area and the intensity of the incident plan sound wave). Interferometric sonar systems combine acoustic bathymetry with simultaneous side scan measurements to provide two co-registered, well positioned images of bathymetry and backscatter.

# VI Mapping land cover in coral reef environments

Remote sensing capability for mapping the benthic cover of coral reef platforms has been well established over the last 50 years, with many sensors operating in the visible section of the electromagnetic spectrum (400 – 700 nm) that are able to penetrate up to 25 m deep in clear waters. The different uses to which these optical sensors have been put include mapping the presence or absence of coral, community classes, coral community health indicators, such as bleaching extent or algal cover (Holden et al., 2001; Elvidge et al., 2004; Yamano and Tamura, 2004) and the detection of changes (Andréfouët et al., 2001; Macleod and Congalton, 1998). From an extensive global collection of reflectance data, Hochberg *et al.*, (2003) demonstrated that the majority of reef components can be spectrally grouped into the following 12 fundamental categories: brown, green and red fleshy algae; calcareous and turf algae; brown, blue and bleached coral; gorgonian/soft coral; seagrass; terrigenous mud; and sand. The spectral discrimination achievable from satellite remote sensing datasets is typically sufficient to differentiate between basic reef components, such as coral, algae and sand, but not individual species (Joyce and Phinn, 2002).

Common reef island plant associations include littoral communities dominated by *Tournafortia* or *Callophylum*, continuous cover of low herbs and grasses, monospecific scrubs (*Aegialitis annulata* or *Avicennia marina*), Pemphis scrub, mangroves, mixed mosaics of low shrubs, herbs, vines and grasses and denser woodland often dominated by *Pisonia* and modified vegetation (Stoddart and Fosberg, 1991). These can be reliably mapped using a combination of automated unsupervised classification and contextual editing based, for example, on the tendency for littoral communities to occupy island peripheries (Chauvaud et al., 1998).

Other reef top and intertidal vegetation characteristics that can be mapped from remotely sensed datasets include mangrove species composition, foliage or canopy cover and above-ground biomass of seagrasses (Phinn et al., 2008; Heumann, 2011). Misclassification of seagrass arising from spectral confusion with other dark features such as coral reefs, blue-green algae, detritus and deep water is common (Mumby and Green, 2000). The incorporation of *in-situ* ground verification is the most reliable way to resolve this. Mangroves can also be mapped using vegetation indices or band ratios that manipulate individual bands of satellite imagery to yield composite spectral bands (Green et al., 1998). Detailed information such as leaf area index and percentage canopy cover can be mapped in this way from hyperspectral sensors, such as the compact airborne spectrographic imager (CASI) (Green and Clark, 2000). Given that much of this coastal vegetation cover lies beneath the water, the application of terrestrial forest remote sensing, particularly using hyperspectral datasets (e.g. the Hyperion satellite sensor) presents an opportunity to further develop techniques for mapping mangroves (Heumann, 2011).

# VII Monitoring island geomorphic changes

Reef islands are low-lying accumulations of unconsolidated sediments derived from the communities inhabiting the reef platform and reworked by waves and tidal currents up onto the reef flat (Flood, 2011). These sedimentary landforms are often vegetated with a mixture of trees, shrubs, hedges, herbs and grasses, which introduce humus soil, adding to the binding and stabilisation of associated root systems (Heatwole, 2011). The societal value of reef islands is evident from the nature of research that has been applied to reef island evolution (Kench et al., 2005). This includes an exploration of environmental influences on reef island dynamics (Hamylton and Puotinen, 2015), interactions between reef ecology and island sediment dynamics (Perry e*t* al., 2011), reef island shoreline change (Webb and Kench, 2010; Hamylton and East, 2012; Purkis et al., 2016), reef island resilience and vulnerability to anthropogenic and natural disturbances, including climate change (Woodroffe, 2008; Kench and Brander, 2006).

Geomorphic changes on reef islands can be driven by fluctuations in constructive and destructive processes such as wind-induced waves and storms (Stoddart et al., 1978a; Flood, 1986; Stoddart and Steers, 1977), cyclones (Scoffin, 1993; Hubbard, 1997) and changing sediment dynamics due to coastal development (Flood, 1979). Island shoreline movements are also driven by natural seasonal sediment fluctuations, onto or away from islands or along beach sections in the form of longshore drift. These collective fluctuations depend on multiple environmental influences that often occur across timescales that are amenable to detection using remote sensing techniques. Often physical proxies such as the edge of the vegetation line or beach toe are used to define shorelines for the purpose of tracking changes in shoreline features over time.

Multi-temporal archives of historical aerial photography and satellite images have been used to observe horizontal shoreline advance or retreat of reef islands through comparison of island outlines. These rely on controlled mosaics that correct for the tilt and magnification of aerial photographs, alongside photogrammetric orthorectification of variable perspective effects across a field of view to enable accurate distance measurements to be extracted from air photos (Crone, 1966). At Heron Island on the southern Great Barrier Reef, Flood (1986) used aerial photography to observe cay migrations with seasonal wind patterns, with southeasterly winds (between February and August) driving the cay leeward, to the northwest part of the reef and movements in the opposite direction in response to northwesterly winds (between September and January). Elsewhere on the Great Barrier Reef, analysis of aerial photography has revealed consistent minor oscillatory motions in oblongate spit orientations at Heron island (Flood, 1974)), Erskine Island (Flood, 1986), Low Isles (Stoddart, 1978) and Gannet Cay (Flood and Heatwole, 1986). Such studies are not restricted to reef islands, indeed, similar techniques were applied to map loss of structure in 20 fringing reefs due to storm damage and alterations in beach morphology in Barbados (Lewis, 2002).

## *7.1 Feature-based assessments of reef island change*

Feature based approaches to change assessment identify and compare discrete entities of interest (e.g. points, lines or polygons) in multiple images taken at separate points in time.

The widespread use of aerial photographic records to analyse changes to horizontal features such as shorelines is evident from the range of software developed designed to interrogate planimetric boundary datasets derived from multiple digitisations of the shoreline, including the Digital Shoreline Analysis System (DSAS) (Thieler and Danforth, 1994) and the Analysing Boundaries Using R (AMBUR) (Jackson, 2010). Limitations associated with the multi-temporal analysis of aerial photographs to monitor island changes over time include the differing resolution or quality of images (Anders and Byrnes, 1991), poor condition of negatives and the fact that historical images were seldom acquired for this purpose and associated flight angles and paths, exposure, coverage and elevation are seldom optimal for this purpose (Webb and Kench, 2010). Furthermore, the visual interpretation of images to ascertain longer term shoreline changes must account for variability in horizontal vegetation structure, such as the degree of canopy overhang, variable water submergence due to the tidal height at the time of image capture and seasonal fluctuations in shorelines. It is also often quite difficult to distinguish poorly defined boundaries between sandy beaches, bars and spits and the reef flat upon which they often sit. Nevertheless, in many geographic areas they offer the best opportunity available for determining reef island change over time.

## *7.2 Raster-based assessments of reef island change*

Beyond the manual digitisation of features from their visual interpretation on photographs, semi-automated raster based methods can be used to detect changes based on a continuous surface, usually composed of a pixel grid, using automated techniques. Techniques for comparing raster images to detect change include image differencing, image regression, comparison of image-derived vegetation indices, principal components analysis change vector analysis and post-classification comparison (Hamylton, 2017)

The Normalised Differential Vegetation index (NDVI) is an example of a raster-based index that indicates the amount of vegetation falling inside each pixel. It calculates the difference between reflectance of bands in the near infrared (high reflectance) and the red (low reflectance) regions of the electromagnetic spectrum. Reflectance values on either side of the steep “red edge” of a vegetation reflectance signature are differenced to provide an index ranging between -1 to 1 for which high values indicate pixels with greater vegetation content than lower values (Rodgers III et al., 2009). This can be generated from any multispectral imagery that has bands corresponding broadly to red and near infrared wavelengths.

## *7.3 Volumetric assessments of reef island change*

Combining information in the horizontal and vertical plane allows island volumetric changes to be assessed. Until recently, coral reef geomorphologists have traditionally based studies of beach erosion and accretion, sediment transport and budgets, and island movement dynamics on repeated topographic profiling and shoreline mapping. LiDAR mapping has allowed analysis of beach and dune microtopography along the land to water interface. Repeat surveys allow continuous, synoptic volumetric change analysis and the quantification of local sediment budgets (Liu et al., 2007). The application of LiDAR technology to reef islands is uncommon as a result of the expense associated with these surveys. Surface elevation measurements have alternatively been derived from aerial photographs using a stereo-plotter to employ digital photogrammetric methods (Yamano et al., 2006), or from beach profile surveys, with interpolation of point measurements using triangulated irregular network techniques to derive continuous digital models of terrain and elevation (Biribo, 2012).

Photogrammetry is advantageous as a source of elevation information because as it can be applied to a longer time series of historical aerial photographs to elucidate topographic changes. Although these approaches are still subject to the image quality issues associated with aerial photography, the vertical accuracies attained have typically been around +/−100 mm in height, which is acceptable for monitoring broad scale fluxes in sediment volume (Yamano et al., 2005). Similarly, the waterlines around reef flat features such as ridges and cemented rubble and pavements can be extracted by interrogating individual wavebands of satellite images with comparable horizontal errors (Yamano, 2007). Structure from motion approaches to topographic estimation from photographs taken by drones (UAVs) also has have the potential for increased application on coral reefs. Although they are increasingly being applied to monitoring changes in other coastal landscapes, such as storm-driven boulder movements (Pérez-Alberti and Trenhaile, 2015), volumetric changes to sand dunes (Guillot and Pouget, 2015) and beach shoreline erosion (Rovere et al., 2014; Casella et al., 2016; Casella et al., 2014), their application in coral reef environments has been limited.

# VIII Modelling from maps to inform management

Digital maps are increasingly being used as geographically referenced data for models that seek to explain or predict spatial patterns across coral reef environments (see Table 2). Such uses call for a redefinition of digital maps as datasets that capture the functional context in which coral reef processes occur (Spencer et al., 2008). They provide opportunities to model relationships between variables corresponding to aspects of process and those reflecting some measure of system response, as represented by the mapped form of the landscape. Within this modelling framework. The form of landscapes can be quantified through metrics associated with individual patches discernible in maps, and the collective, scaled up metrics of assemblages can be interrogated across gradients (Frohn, 1997). Such an approach is particularly useful in coral reef environments that traverse a range of different environmental settings and gradients. For example, the forereef and lagoon areas are subject to different levels of wave energy. By interrogating the properties of a digital map at different locations along such environmental gradients, it is possible to explore how wave energy (as an independent, environmental variable) influences the form of a coral reef environment (as a response, dependent variable). In this way, an explanatory model can be constructed that attempts to explain the form of the landscape as a response to processes occurring in the local environment. A predictive model may further utilise the empirical relationship defined by an explanatory model to extrapolate predictions of benthic habitat or species cover over larger spatial or temporal scales (Guisan and Zimmermann, 2000; Brown et al., 2011).

# IX A case study of Low Isles, Great Barrier Reef

## *9.1 Mapping the Low Isles reef environment*

On a global scale, Low Isles is *'believed to be unique in the study of coral islands'* (Fairbridge and Teichert, 1948: p 67) because of the long history of mapping activity that has taken place there. Figure 4 presents a series of maps of Low Isles ranging from 1928 to present. The *'physiographical sketch map'* (Figure 4a; Steers, 1929) outlines the major features of the low wooded island for the purpose of discussing island formation. This basic map was made by E.C. Marchant during the 1928-1929 *Great Barrier Reef expedition* using a plane-table (Debenham, 1936; Debenham, 1956). The level of detail shows individual Rhizophora along the expanding face of the mangrove swamp "Woody Island" on the reef flat. Difficulties associated with this technique included the reliance on correct orientation of the table at each sighting station and the limited vertical range of the sighting alidades. The basic set-up employed by Marchant commonly produced a map that lacked correspondence between three or more ray intersections for a given point of interest, raising questions about the accuracy of this technique (Debenham, 1937). It was therefore quickly supplemented with a theodolite, which enabled more accurate triangulation of features and the plotting of finer details.

Perhaps one of the best known maps of Low Isles is that produced by M.A Spender, also during the 1928-1929 *Great Barrier Reef Expedition* by theodolite triangulation. This map was also based on the first aerial photographs of Low Isles, which were flown in September 1928 at a scale of 1:2400 (Figure 4b). Synoptic information on land surface cover was combined with triangulated networks of features to generate continuous maps of reef surface cover. Swathes of shingle, boulders, sand and mud could be delineated and filled in on a reef flat, while features such as the outer boundary of the reef perimeter, channels and shingle ramparts could be fixed by triangulation (Figure 4b). Details were transferred from the aerial photograph to the map by tracing discernible boundaries by hand from the air photograph. This is the earliest known record of ground observations being cross-referenced against aerial photography for the purpose of reef mapping. Although this represents a major innovation, the widespread use of aerial photography for detailed reef mapping was not realised until later (Steers, 1945).

The level of detail incorporated into Spender's (1929) map is remarkable given the elementary field techniques with which it was made. Detail was likely enhanced through cross referencing against aerial photography. Outlines of individual reef patches are apparent along the northern shoreline of the reef platform, which correspond closely to outlines of the same reef on aerial images. Beachrock features are included around the periphery of the sand cay, providing a useful record of distinctive and recognisable immobile features against which ground control can be established to bring the historical map into a spatial frame of reference with contemporary records of aerial photographs and satellite images.

A detailed compass and measuring tape survey of Low Isles was carried out over a three day period during the 1973 Royal Society and Universities of Queensland Expedition to the northern Great Barrier Reef. This was the only one of 54 islands visited that was mapped with a measuring tape to enhance accuracy because one of the key objectives of this mapping campaign was to elucidate changes in island topography, shingle ramparts, conglomerate platforms and mangrove swamps in the period since the reef was mapped by Spender (Figure 4b) (Stoddart et al., 1978b). Areas that were not of interest remained blank (e.g. the extensive reef flat between the sand cay and the mangrove swamp).

Figure 4c and 4e illustrate sketches made from aerial photographs based on visual interpretation and digitisation of features such as the outline of the mangrove swamp by tracing over them on a screen. By deriving repeat sketches over time, changes such as the retreat of the shingle ramparts and extending ridges of coral debris associated with storms can be monitored (Frank and Jell, 2006).

## *9.2 Mapping the Low Isles sand cay topography*

Figure 5a illustrates a digital elevation model of the sand cay at Low Isles that were constructed by applying structure from motion techniques to images collected by drone surveys flown at 60 m and 120 m altitude respectively. The three dimensional character of the sand cay was reconstructed from a series of photographs through feature matching and triangulation using the photogrammetric software Agisoft Photoscan Professional (AgiSoft, 2014). This approach detects and matches clearly visible points representing the same feature from at least three perspectives under different lighting conditions. Approximate positions for each photo are measured from the drone GPS, with ground coordinates estimated for a given flight altitude. Triangulation adjusts for camera orientation and focal length to produce a point cloud, which is then processed into a continuous mesh. To further improve locational accuracy, ten visible targets were established around the cay as ground control points, for which x, y and z coordinates were measured with a differential GPS (accuracy +/- 10 cm). A georectification was performed to bring the digital elevation models into line with the ground control points. Both elevation models were then compared to an independent set of 22 height measurements taken from discernible features around the island, including buildings corners, the lighthouse and trees.

Figure 5b compares the two elevation models to reveal that the structure from motion approach performs best on the images collected at the lower altitude, producing a mode detailed model of higher accuracy. This is because flying the drone at a lower altitude results in an image with a narrower ground footprint for a given focal length and sensor width. More images are therefore required to cover the same survey area, resulting in a greater amount of image overlap. This means that more can be reliably matched, resulting in a digital elevation model based on a greater number of tie points with a higher spatial resolution and a more precise estimate of elevation for a given ground area.

Although flying the drone at a lower altitude results in higher quality images, it is impractical to survey large areas (i.e. > 100 m across) at low altitudes because of associated increases in the time and battery power required for the survey and also the amount of images acquired and processed. Figure 6 illustrates a mosaic of 6762 images acquired from an aerial survey of Low Isles reef system flown at 120 m altitude over a three day period. During this time, multiple smaller surveys were undertaken that accounted for variable weather windows within which the drone could be flown, restrictions on the maximum distance that the drone could fly both from the operator and between adjacent flight lines and battery capacity (approximately 15 minutes flight time per battery for a Phantom DJI 4). As a point of comparison, the images of the sand cay collected at the same altitude took approximately 8 minutes, suggesting that drones are a useful technology for conducting aerial surveys of smaller features within reef systems, as opposed entire reef platforms.

In 2009, the Queensland Government, on behalf of the Cairns Regional Council, undertook LiDAR surveys of the inshore reef islands under the Tropical Coastal LiDAR Capture Project. The purpose of the survey was to provide highly accurate elevation data for use in risk assessment, management of natural disasters, infrastructure planning and developing strategies to support climate change. Because of the high cost of LiDAR, islands that were sites of infrastructure development were therefore prioritised (i.e. at Low Isles, the sand cay was included, but not Woody Islet). Figure 7 a illustrates the 1 m digital terrain model (DTM) derived by interpolating the LiDAR point cloud, with associated terrain profiles across the cay (Figures 7b and 7c). A key distinction between this DTM of the sand cay and the DEMs generated by applying structure from motion techniques to the drone images is that the vegetation of the cay has been removed, revealing the surface topography of the cay. This was achieved by analysing multiple returns from the light pulses emitted by the active LiDAR sensor, specifically by comparing the first and last returns to establish and remove the height of the vegetation from the DEM. On reef islands, such topographic models are informative as they often show ridges and banks that coincide with storm deposits, revealing the processes that underpin the geomorphic evolution of the island.

## *9.3 Monitoring changes to mangroves on the Low Isles reef flat*

Several studies have sought to assess changes to the geomorphic features of the Low Isles reef system such as shingle ramparts and island shorelines to reveal clues about reef platform evolution in relation to longer term environmental controls, such as sea level. A key feature of the Low Isles reef flat that has received attention over the last ninety years is the extent to which the reef surface has become colonised by mangroves, which indicates the nature and sequence of processes responsible for the current reef landforms structures.

Both raster and vector based approaches can be used to assess the extent to which the mangrove cover on the reef flat has changed. In terms of a raster based analysis, Figure 8 illustrates the NDVI index calculated from three different Landsat images (MSS, TM, or ETM+) of Low Isles. The gradual expansion of yellow and green pixels indicates growth of vegetation across the reef flat. In contrast, a feature based approach illustrated by Figure 9 evaluates change across a series of transects adjacent to the shoreline, along which a statistical dataset of repeated change measurements can be built up.

## *9.4 Modelling the distribution of foraminifera around Low Isles*

An explanatory model seeks to explain the reasons for a given observation in the natural world, usually by expressing this as a function of one of more influential, driving variables (Hamylton, 2017). In this case, a preliminary explanatory model expressed the relationship between 50 mapped samples of the sediment foraminiferal content (Schueth and Frank, 2008) and influential environmental conditions. Specifically, a spatial regression model was used to define an empirical relationship between foraminiferal content (dependent variable) and local environmental setting, defined by a multivariate function composed of three independent variables: the presence of algae habitat upon which many large benthic foraminifera rely, aspect relative to the mainland and pixel sand content (represented by proxy using the pixel reflectance). These relationships have a distinct influence on the spatial distribution of foraminifera at Low Isles and are evident in the map. This was then used as a basis for predicting the percentage foraminifera content of carbonate sands around the Low Isles reef system (Figure 10). This statistical relationship was employed to further predict the distribution of foraminifera at unsampled locations around the Low Isles reef system using spatial regression. Such explanatory and predictive spatial modelling exercises demonstrate the value of digital maps as datasets that can help us better understand coral reef environments.

# X Conclusions and future opportunities

The technology available for mapping coral reefs has incrementally improved since the 1920s, with resulting gains in the efficiency of mapping campaigns and the quality of information presented in maps (e.g. completeness, consistency, accuracy, resolution and measurement level). Table 3 summarises the major advances in both instrumentation for collecting spatial information and methodological approaches for interpreting it. These advances have been supported by two major technological developments in the form of GPS and earth observation remote sensing. These respectively have brought about the ability to rapidly and accurately locate oneself directly in the field, and to generate broad scale, synoptic mapping of large areas. In turn, this has enabled the extrapolation of field effort and made large scale campaigns possible in spite of the practical constraints associated with working in remote environments.

Perhaps one of the most exciting opportunities arising from advances in the resolution of remote sensing imagery is the enhanced levels of detail to which small features can be observed. These are now commensurate with the scales over which physical and biological processes occur and leave their physical expression in coral reef environments. For example, surveying from a camera of sensor width 4mm, focal length 15 mm at an altitude of 50 m would yield digital photographs with pixels of spatial resolution 0.33 cm and an image footprint of 10 m wide on the ground. It is therefore possible to see individual corals and resolve their growth form. It follows therefore that the dynamics governing the spatial patterns in coral reef environments, and the interplay between process and form, can also be digitally recorded and interrogated.

Innovative methods for deriving useful information from the images they collect continue to emerge. For example, airborne fluid lensing techniques capitalise on the challenges presented by the water surface to exploit time-varying optical lensing effects on light as it passes through the waves on a water surface. These have successfully been applied to reefs in American Samoa and Shark Bay (western Australia) to distinguish coral, fish and invertebrates (Chirayath and Earle, 2016). Such a step could potentially be transformational because for the first time it allows the underwater features of coral reefs to be resolved in sufficient detail that individual coral colonies can be mapped across larger areas, i.e. those commensurate with entire coral reef platforms (15km$^2$).

Other technological developments that hold promise for mapping in coral reef environments include autonomous underwater vehicles and orbital LiDAR. Autonomous underwater vehicles (AUVs) enable collection of georeferenced parameters such as bathymetry, backscatter, current regime, sub-bottom profiles and measurements of chemical-physical water properties on previously inaccessible forereef areas and deeper reef terrace environments (Grasmueck et al., 2006). Because they collect information closer to the seafloor, they have the benefit of much higher spatial resolutions (ca <1 cm). Satellite based orbital LiDAR has the potential to vastly expand the quantity of data collected over larger areas to map the topography of the Earth's surface, and applications across broad geographic areas of the Brazilian savannah have shown promise (Ferreira et al., 2011). While this is currently restricted to terrestrial wavelengths, marine instruments will likely be developed in the future.

Digital maps are increasingly being used to develop a variety of different models (see Table 1), These may be used to upscale measurements of seafloor character and associated goods and services (e.g. the calcification of coral reef communities) to broader geographical areas and associated functional units such as entire reef platforms; to construct explanations for spatial patterns observed across coral reef environments (e.g. explaining community zonation patterns in terms of localised environmental settings); or to predict future distributionds of features within coral reef environments (e.g. the landward erosion and seaward accretion of island shorelines). To this end, maps are increasingly being understood as valuable datasets that complement other types of information such as coral growth rates derived from radio carbon dates or lab-based growth experiments to specify cross-disciplinary models that further our understanding of spatial patterning.

Mapping lies at the heart of spatial analysis and as digital maps have become increasingly widespread, their utility has gone beyond simply undertaking a large scale inventory of coral reef environments to track how these are changing over time and model the remarkable spatial patterns in these environments. Digital maps therefore represent the beginning of a line of enquiry, as opposed to the end of a mapping exercise. As associated technologies improve access to high quality information, they will continue to be a critical source of information to reef managers, scientists and conservationists.

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## Figure captions

Figure 1 Schematic representation of the hierarchical framework increased analytical depth for utilising spatial information on coral reefs from mapping to monitoring to modelling.

Figure 2 Collecting primary spatial data in coral reef environments: (a) A snorkeler towing a GPS along in a floating waterproof bag while taking ground referencing photographs above a coral reef (b)scuba divers collecting spectral signatures of the seafloor to support broader scale mapping using remote sensing techniques (c) collecting ground referencing information by lowering a video camera down from a boat (Photo credit: Matthew Smith) (d) A coupled GPS monitor and side-scan sonar instrument display attached to a boat (Photo credit: Frank Sargeant).

Figure 3 (a) An oblique image of Low Isles taken by a DJI Phantom 4 unmanned aerial vehicle, (b) Predetermined flight lines for an airborne UAV survey of the sand cay at Low Isles, spacing between flight lines has been determined based on the sensor field of view at an altitude of 90 m, (c) A DJI Phantom 4 drone beside mangroves (photo credit: Mark Newsham).

Figure 4 A series of maps made of Low Isles, Great Barrier Reef (a) Plane-table sketch by E. Marchant (reproduced with permission from Steers, 1929) (b) Theodolite triangulation plane-table sketch by M. Spender (Steers, 1929) (c) Aerial photograph trace (reproduced with permission from Fairbridge and Teichert, 1948), (d) Compass-traverse survey (supplied by D. Stoddart) (e) Aerial photograph sketch (reproduced with permission from Frank and Jell, 2006), and (f) Satellite image classification by the author, 2014.

Figure 5 A An oblique view of a digital elevation model of Low Isles sand cay constructed by applying structure from motion photogrammetric processing to 140 images collected from an aerial drone survey at 60 m altitude. B. Two digital elevation models of Low Isles sand cay constructed using photogrammetric structure from motion techniques on images collected by a drone at altitudes of 60m and 120 m respectively. The survey at a lower altitude produced a digital elevation model of greater precision, showing more detail at a higher accuracy.

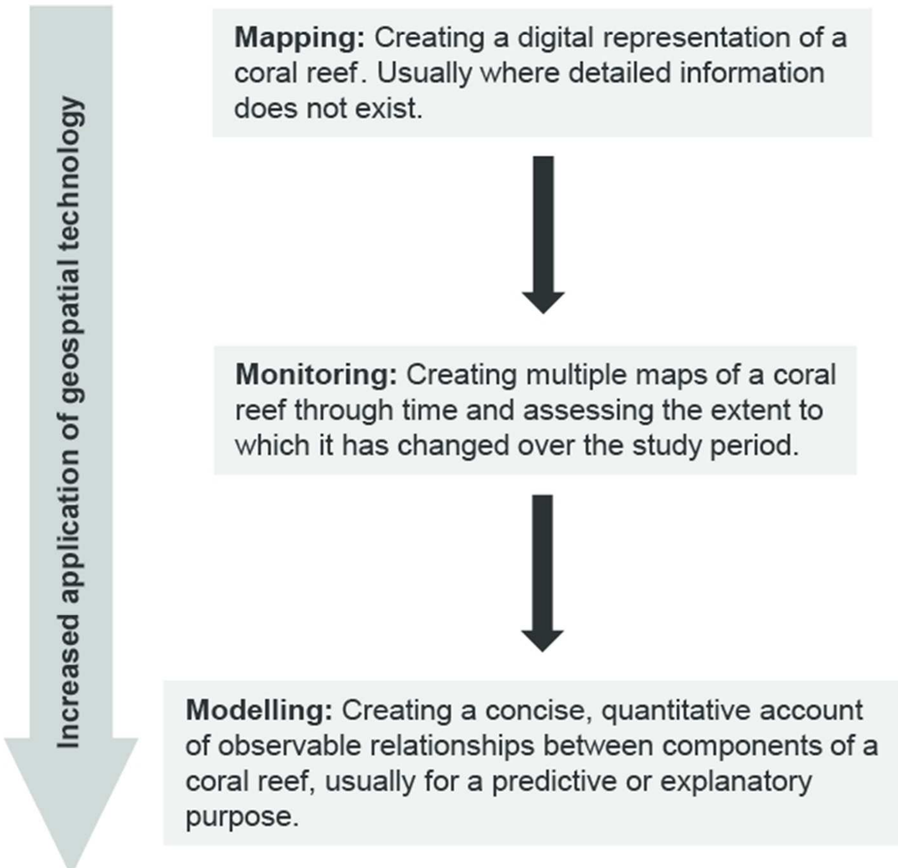
Figure 6 An orthophotomosaic of 6762 aerial images collected during a three day drone survey of the Low Isles reef system at an altitude of 120 m. Insets illustrate some common features of coral reef environments that can be distinguished from the high resolution imagery (2.6 cm pixels). A Beachrock, B Mangrove roots, and C Porites microatolls.

Figure 7 A three-dimensional Digital Elevation Model (DEM) of the sand cay at Low Isles derived from an airborne LiDAR survey (see Figure 2c for an indication of the location). (a) complete DEM of the sand cay, (b) and (c) illustrate vertical planar profiles for transects 1 and 2 respectively.

Figure 8 Normalised Differential Vegetation index (NDVI) calculated for a time series of images of Low Isles, Great Barrier Reef to illustrate the expansion of the mangroves across the reef flat. NDVI is an indicator of the amount of vegetation occurring within a pixel, values range from -1 (lower vegetation content) to +1 (higher vegetation content). Images used in the calculation were (a) Landsat MSS acquired in 1975, (b) Landsat TM acquired in 1995, and (c) Landsat ETM+ acquired in 2015.

Figure 9 (a) An illustrative example of a digital approach to the analysis of shoreline changes, tracking the expansion of the Woody Island, the reef flat mangrove swamp at Low Isles from 1928 – 2012 using 28 transects cast perpendicular to the direction of shoreline movement, (b) Magnitudes of change ranging from 80 m erosion on the eastern seaward rim to 289 m leeward expansion across the reef flat.

Figure 10 An illustrative example of the specification of explanatory and predictive models of the distribution of foraminifera around Low Isles, Great Barrier Reef from a combination of remote sensing imagery and 50 field collected sediment samples of known foraminifera content.

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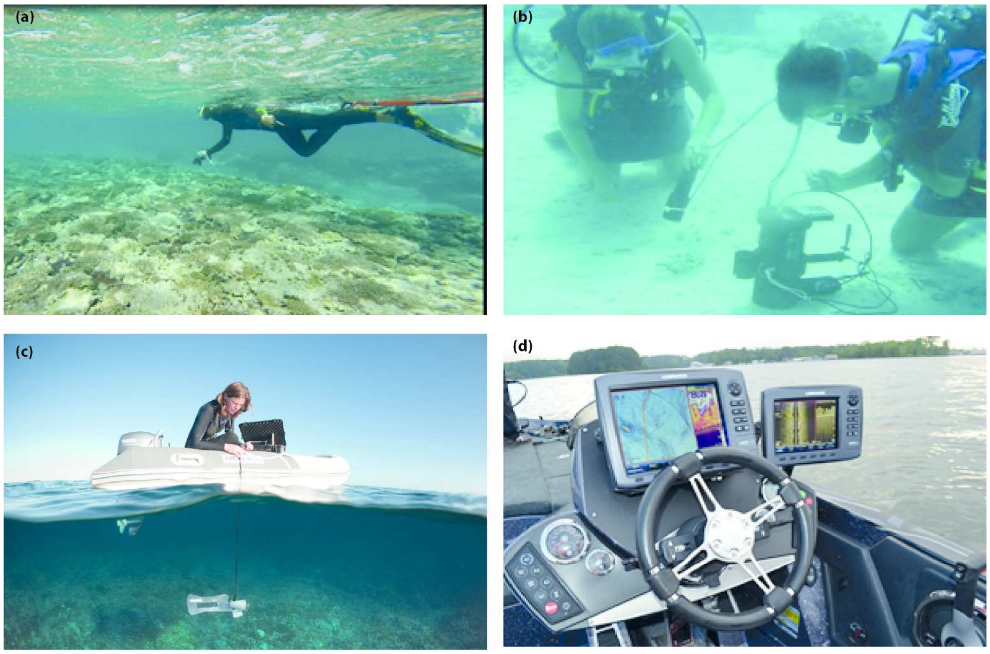


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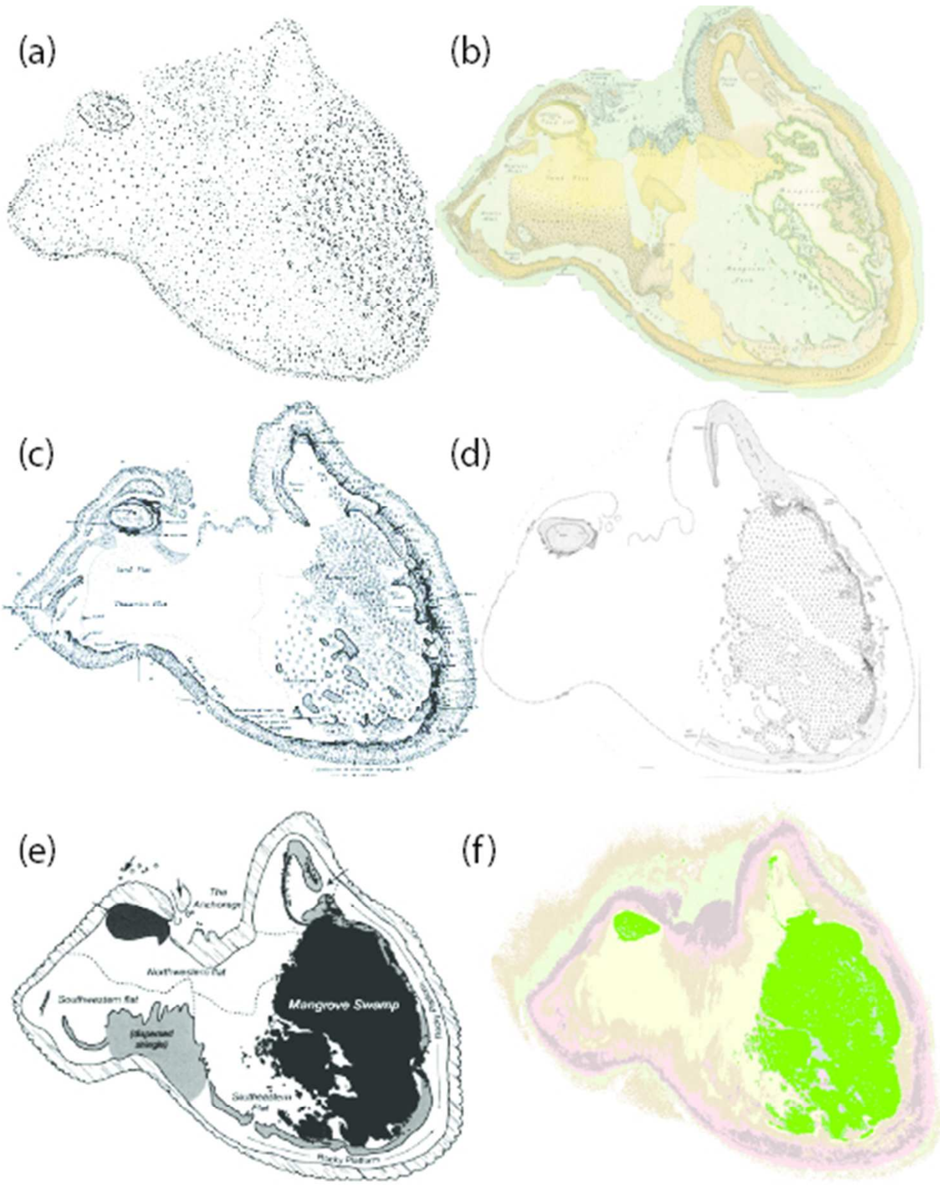
219x220mm (300 x 300 DPI)

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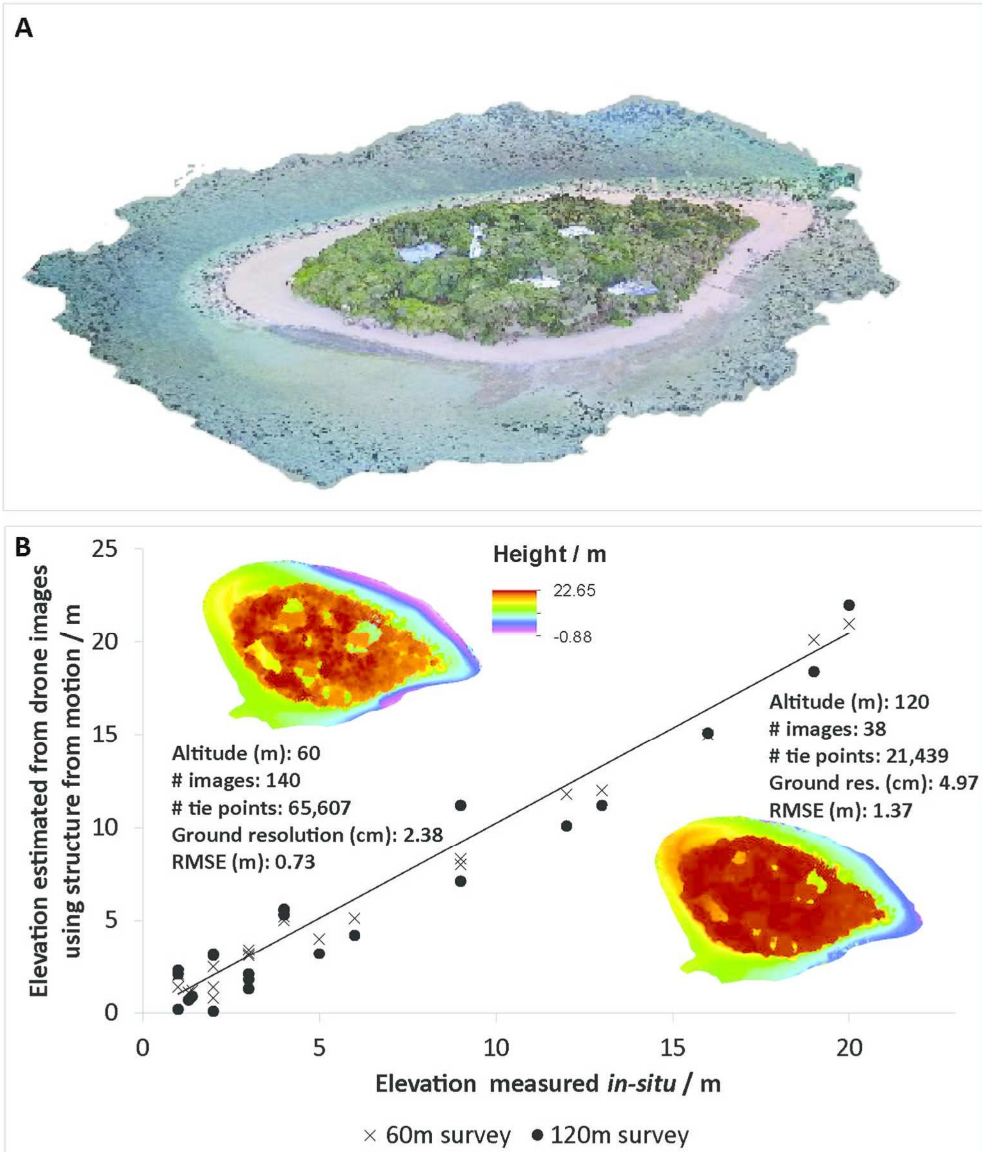


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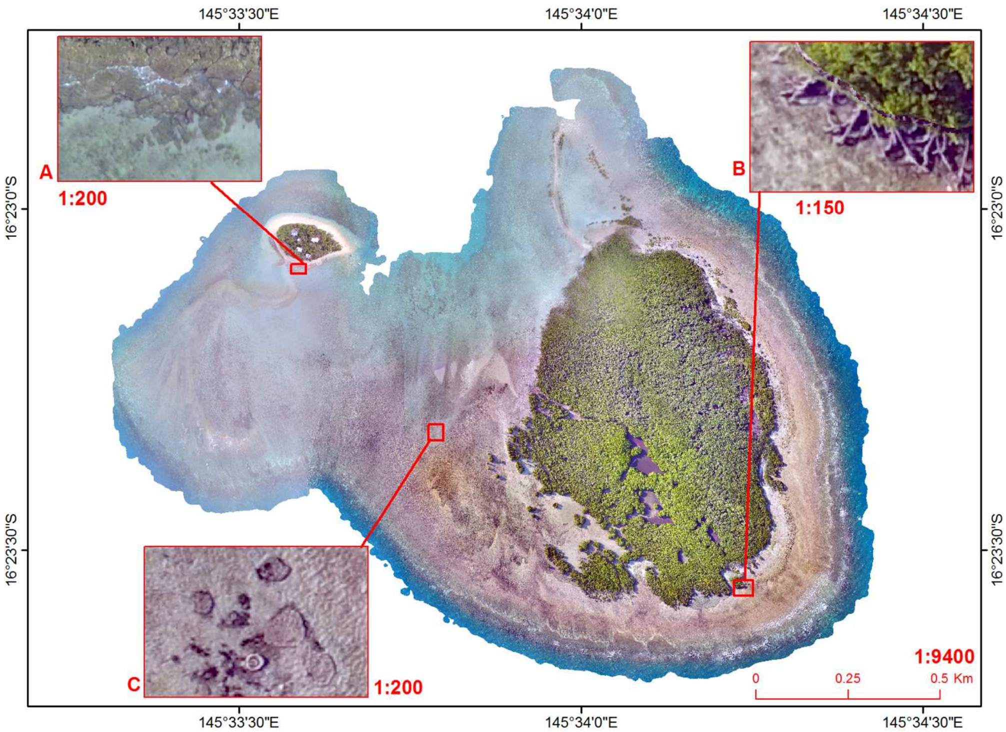


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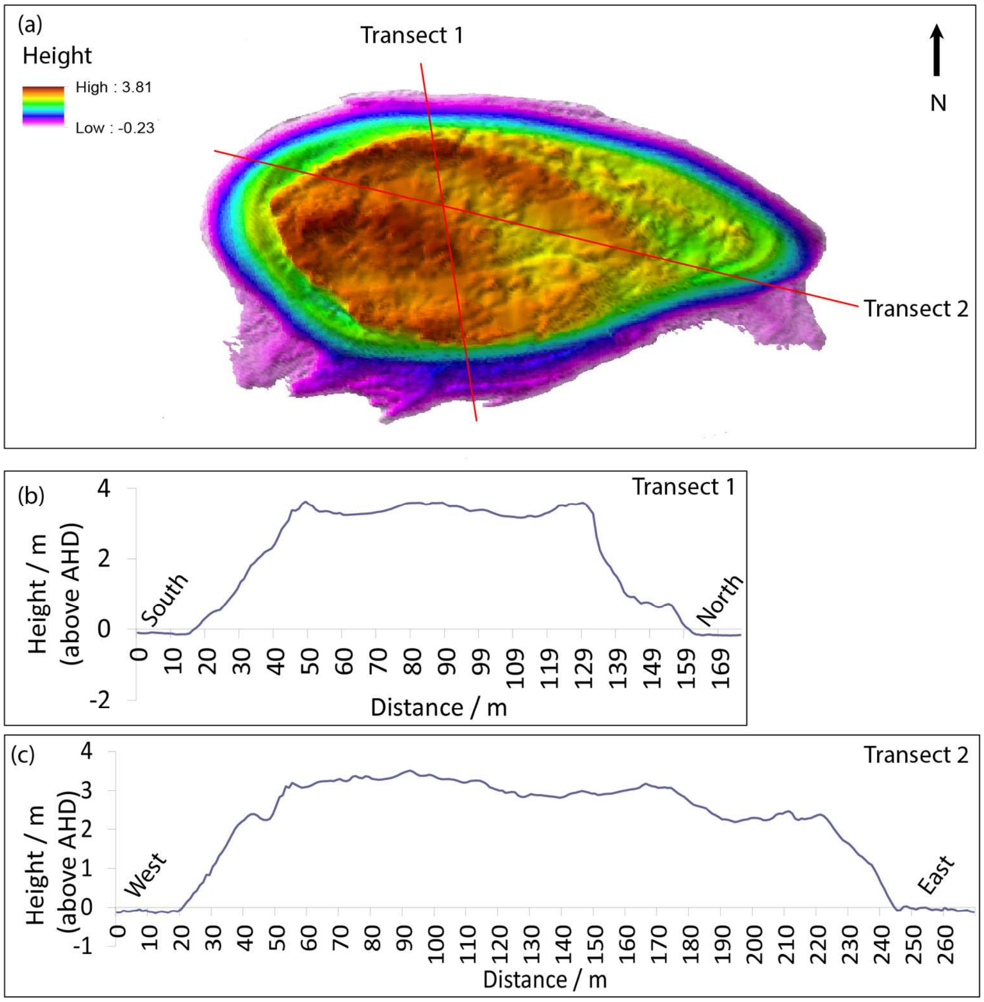


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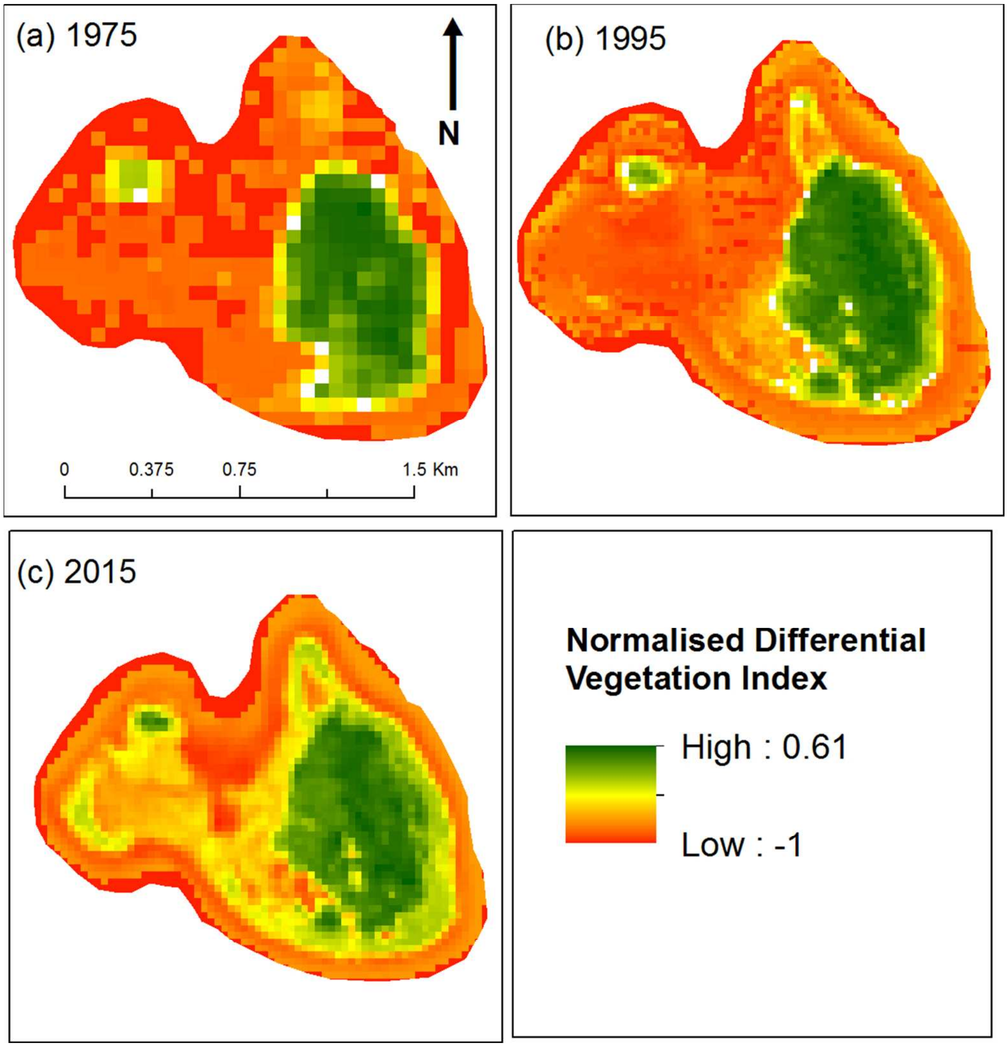


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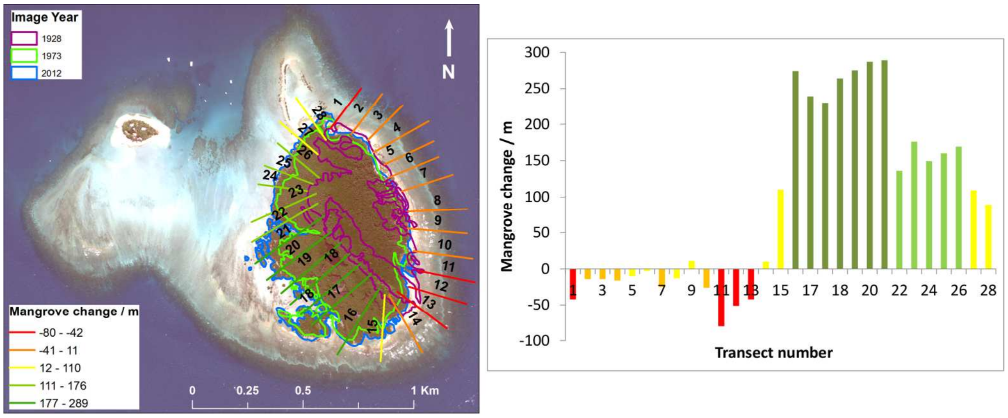


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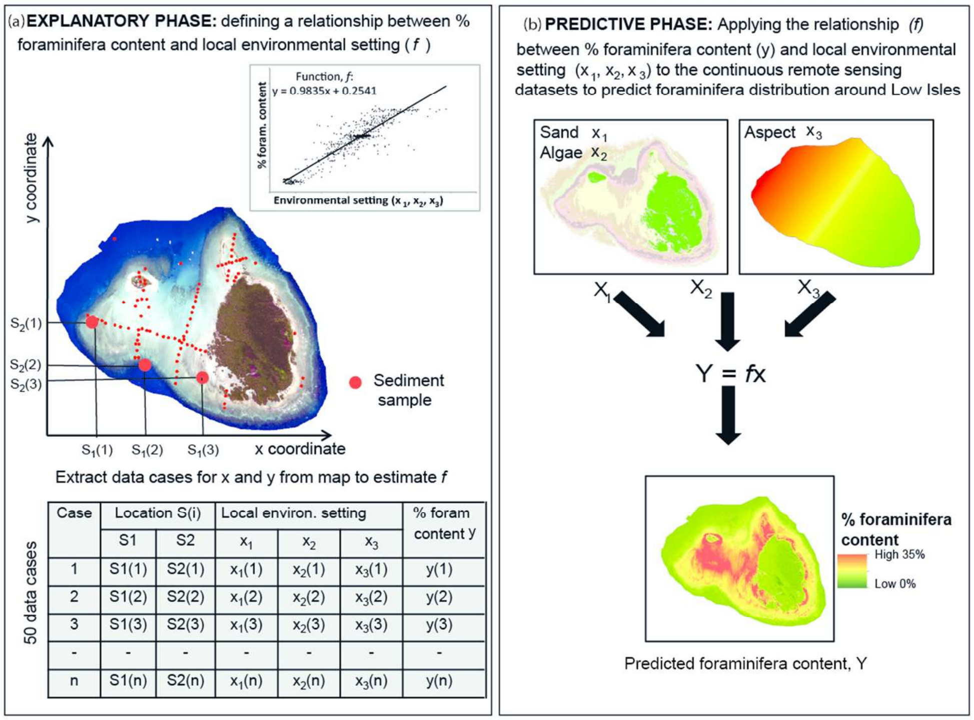


209x153mm (150 x 150 DPI)

Table 1. Summary of mapping techniques applied to reef islands in the early twentieth century.

| Technique | Summary description | Reference |
|---|---|---|
| Plane-table survey | A smooth, flat plane table mounted on a sturdy base is used as a foundation for a drawing sheet, on which objects of interest are sighted and plotted. An alidade, a ruler with a telescopic sight, is used to construct a line to depict the direction and angle of the object to be mapped. | (Debenham, 1956, Debenham, 1937, Debenham, 1936) |
| Theodolite triangulation | Establishment of a network of high accuracy topographic control points using a theodolite to precisely measure angles in the horizontal and vertical planes, from either end of a fixed baseline. Triangulation fixes the location of the point as the third point of a triangle with one known side and two known angles. | (Stoddart, 1978) |
| Aerial photo interpretation | Aerial photographs taken at nadir are aligned in scale with an outline of features plotted from triangulation networks. Boundaries between are traced between and around the features and different surface covers are filled in. | (Frank and Jell, 2006, Hopley, 1978) |
| Compass traverse | Horizontal angles are measured using a prism survey compass and distances, are measured using either a fibron tape, or calibrated paces. Traverses are undertaken as closed circuits and can be subdivided into sectors and related to a primary network. | (Stoddart, 1978) |
| Satellite image processing | Automated image processing algorithms are applied to a satellite image to classify composite pixels into statistically distinct classes based on their reflectance properties | (Goodman et al., 2013) |

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Table 2 Different types of model that are constructed from maps of coral reef environments

| **Model** | **Description** | **Reference** |
|---|---|---|
| Geographically weighted regression | Statically relating the distribution of Spur and groove morphological characteristics (groove length) to relative wave exposure in the Southern Great Barrier Reef, Australia | (Duce et al 2014) |
| Spatial error modelling | Empirical derivation of high resolution bathymetric models of Sykes and Lizard Island reefs from in-situ single beam surveys and optical satellite images | (Hamylton et al., 2015) |
| Spatial autoregressive model | Estimating the cover of live coral across the Al Wajh Bank fringing reef system (Saudi Arabia) from bathymetry, wave energy and the concentration of suspended sediments | (Hamylton, 2012) |
| Species distribution model | Modelling the presence or absence of shallow water seagrass around Lizard Island on the Great Barrier Reef in relation to changes in incident wave energy driven by sea level rise | (Saunders et al., 2014) |
| Landscape ecology | The application of landscape ecology for better understanding ecological connectivity across coral reef systems to help with conservation planning, through addressing questions such as "how much habitat to protect?", "what type of habitat to protect?" and "which seascape patterns provide optimal, suboptimal, or dysfunctional connectivity for mobile marine organisms?" | (Grober-Dunsmore et al., 2009) |
| Cell-based simulations or cellular automata. | Simulating coral reef community dynamics of ten species of Caribbean coral in relation to natural background disturbance events | (Langmead and Sheppard, 2004) |

Table 3. A summary of major technological advances in both technology for the collection of spatial information in coral reef environments and approaches for interpreting and processing this information

| Information collection technology | | |
|---|---|---|
| **Technological advance (year)** | **Advantages** | **Disadvantages** |
| Aerial photography (1928) | • For the first time, coral reef environments could be seen and interpreted from above | • Poor quality of negatives<br>• Aerial photographs taken on oblique, as opposed to vertical, angles |
| Earth Observation satellites (1960) | • Large areal footprint on the ground<br>• Consistent data collected in the form of radiance values per pixel | • Image data are subject to distortions due to the atmosphere and water column |
| Landsat Program (1972) | • Relatively consistent image specifications collected spanning >40 years | • Low spatial resolution (30m) relative to scales of variability in coral reef environments<br>• Low temporal resolution |
| Air and spaceborne hyperspectral sensors (1982) | • Greater spectral information offering a wider range of processing approaches<br>• Ability to resolve a greater range of features accurately | • Large images and associated processing and storage burdens |
| LiDAR (airborne, terrestrial, marine, terrestrial laser scanner) (1960) | • Can generate a reliable digital elevation model or digital terrain model based on first and last pulse returns.<br>• Can be applied to both above and underwater environments | • Expensive to deploy, as LiDAR instruments are typically operated from a plane<br>• Generates large point data clouds, with an associated processing burden |
| Acoustic sensors (1960) | • Can operate in deep water (<1k m)<br>• Simultaneously collects information on water depth and feature texture | • Data require tidal corrections<br>• Comparably low areal footprint |
| Drones (UAVs) (2000) | • User has greater control over survey timing and parameters<br>• Greater spatial resolution of images collected afforded by lower flying altitude | • Drone flights are dependent on favourable weather conditions<br>• Small areal footprint relative to space and higher altitude airborne sensors |
| Autonomous underwater vehicles (1957) | • Greater spatial resolution of images collected just above seafloor | • Small areal footprint due to proximity of sensor to seafloor |
| **Information processing approaches** | | |
| Structure from motion (1975) | • Can reliably model 3D surface characteristics | • Doesn't work through a water surface<br>• Requires specialised photogrammetry software |
| Spectrally based image classification algorithms (1990) | • Can be applied using supervised or unsupervised techniques depending on data availability<br>• Can reliably resolve thematic classes with limited user input | • Requires multiple water-penetrating image bands and specialised image processing software<br>• Land and underwater classifications require different |

| | | |
|---|---|---|
| | | spectral calibrations |
| Fluid lensing (2016) | • Small scale (cm) features can be resolved across large areas (10s kms) | • Limited to underwater environments<br>• Requires optimal wind-generated sea surface wave conditions |